i.e.

$$Z_{thha}(t) = \sum R_{th\nu}\left[1 - \exp(-t/\tau_{th\nu})\right]$$

The number of ν and the $R_{th\nu}$- and τ_ν-values are chosen so that a sufficient approximation of the characteristic can be produced without applying complicated calculation procedures, independent of the physical structure. One iteration method is described, for example, in source [266].

The ratings for simulations indicated by SEMIKRON and mentioned briefly in the following chapters are based on a 4-time-constants-model ($\nu = 4$).

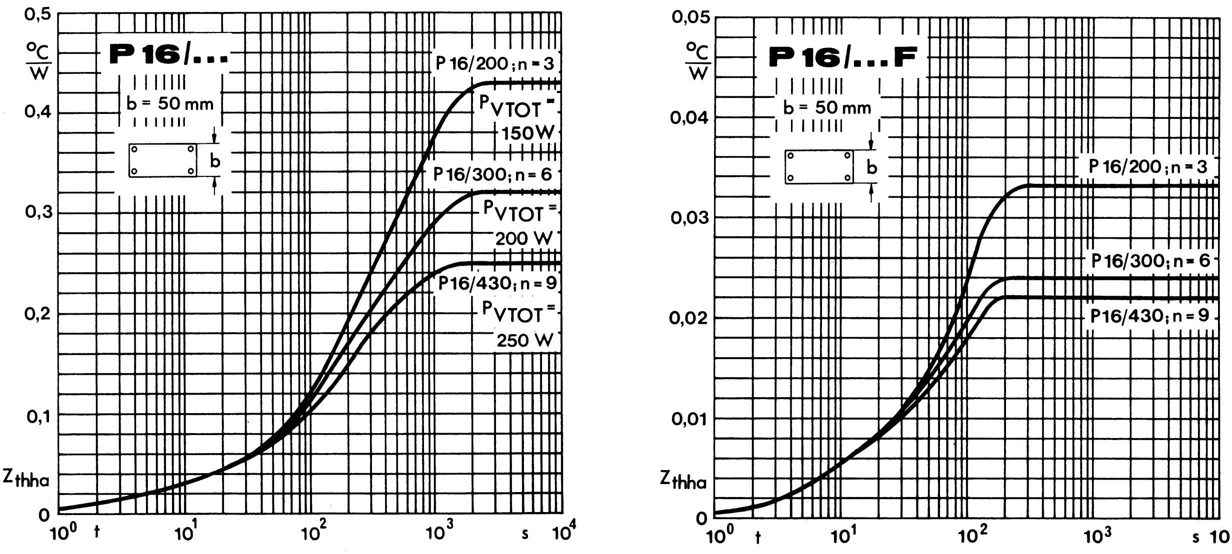
3.3.3 Natural air cooling (free convection)

Natural air cooling is applied in low power range applications up to 50 W as well as in high power range applications, if the use of fans is not possible or if extremely large cooling surfaces are available in the device.

Since with free convection, the thermal transient resistance of the heatsinks usually exceeds the internal thermal resistance of the power modules, the temperature difference between chip (125°C) and cooling air (45°C) drops mainly over the heatsink. Near the modules, the heatsink temperature is usually higher than with forced air cooling, for example 90...100°C. Because power losses are usually low with natural air cooling, heatsink root and fins do not have to be very thick, since heat conductivity has only a minor influence on the thermal features. The fin distances have to be selected sufficiently to obtain a favourable ratio between air uplift (drop of temperature / density) and air friction. Black coating of the heatsink will improve the radiation characteristics and, thus, the R_{thha}-value by about 15 % at a temperature difference of 50 K between mounting surface and atmosphere [266]. The surface finish, however, does not impair heat transfer between module base plate and heatsink.

3.3.4 Forced air cooling

In contrast to natural air cooling, forced air cooling can reduce the thermal heatsink resistance to 1/5...1/15. Figure 3.16 compares the $Z_{thha}(t)$ characteristics of natural and forced air cooling up to the final R_{thha}-value with the example of different SEMIKRON P16/...-heatsinks.



a) b)

Figure 3.16 Z_{thha}(t)-characteristics for different P16/...-heatsinks
a) Free convection
b) Forced air cooling

Compared to free convection, α is much higher with forced air cooling. The rated surface temperature of forced air-cooled heatsinks should not exceed 80...90°C at a supply air temperature of 35°C (condition for datasheet ratings).

The heat conductivity of the heatsink has tremendous influence on the cooling effect, which requires a thick root and a maximum number of fins. Because convection is mainly responsible for the dissipation of heat, black coating of the heatsink will have almost no effects with forced air cooling.

R_{thha} is mainly determined by the rate of air flow per time V_{air}/t, depending on the average cooling air velocity v_{air} and the transfer cross section A:

$V_{air}/t = v_{air} * A$

Instead of the assumed laminar air flow, air whirlings on the fin surfaces will effect turbulent flow conditions between the fins, which will improve heat dissipation to the atmosphere, provided the fin surfaces are set out accordingly.
The transfer cross section of the heatsink will be reduced by increased number of fins and fin width as well as by increased heatsink length (fin length L) and the cooling air-pressure drop Δp will rise. Consequently, heat dissipation is dependent on the characteristics of the fan, which are described in the fan characteristic $\Delta p = f(V_{air}/t)$ (Figure 3.17).

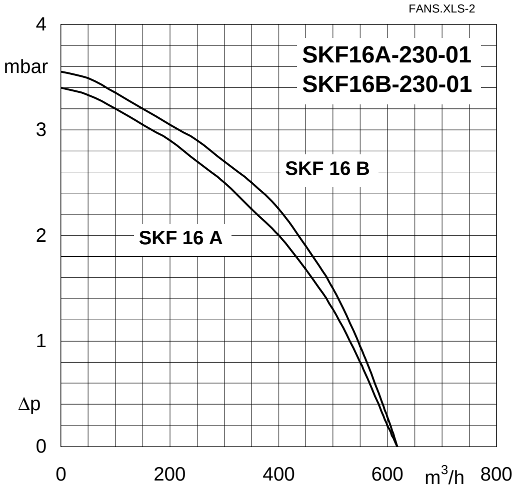


Figure 3.17 Fan characteristic $\Delta p = f(V_{air}/t)$ for SEMIKRON P16/... fans

The thermal transient resistance of the heatsink assembly R_{thha} depends on the rate of air flow shown in Figure 3.19, which may be determined by combining fan and pressure drop characteristics $\Delta p = f(V_{air}/t, L)$ or $\Delta p = f(v_{air}, L)$ of the heatsink.

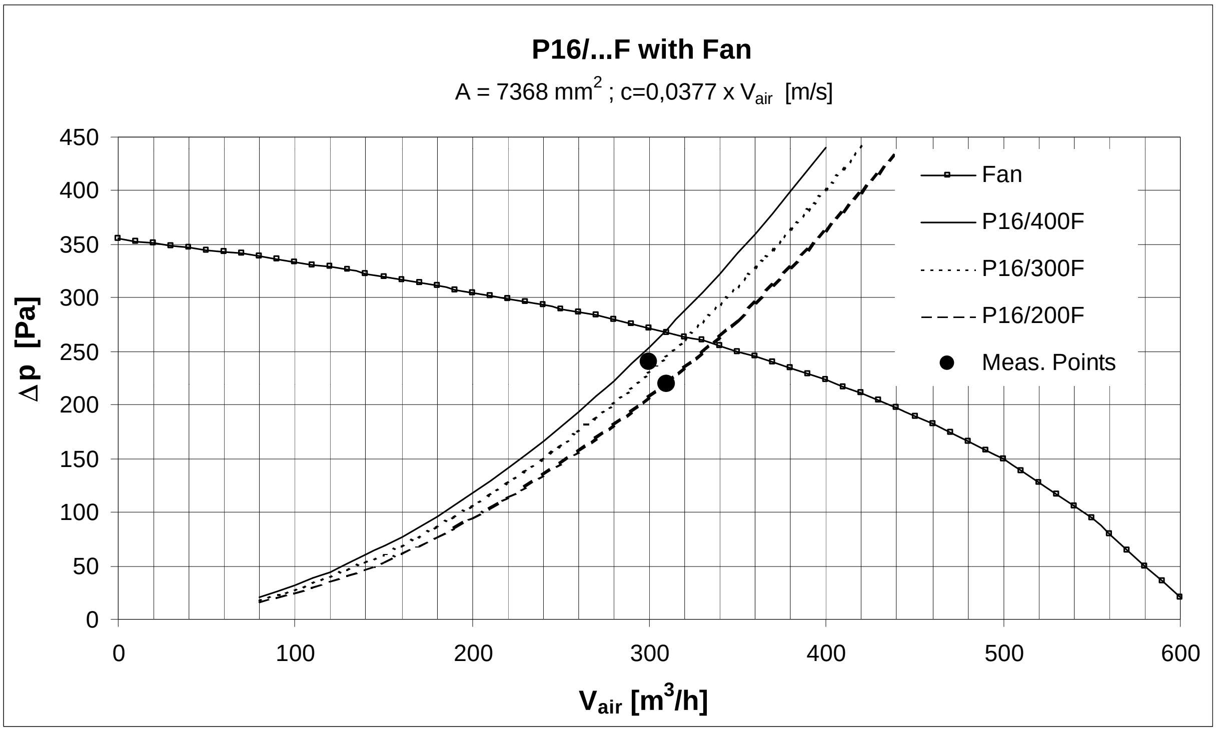


Figure 3.18 Air flow of a P16/... heatsink profile at various heatsink length

Apart from the air flow, R_{thha} is dependent on distribution and position of heat sources (power modules) on the heatsink. Figure 3.19 explains these relationships with the example of a selected SKiiP-assembly.

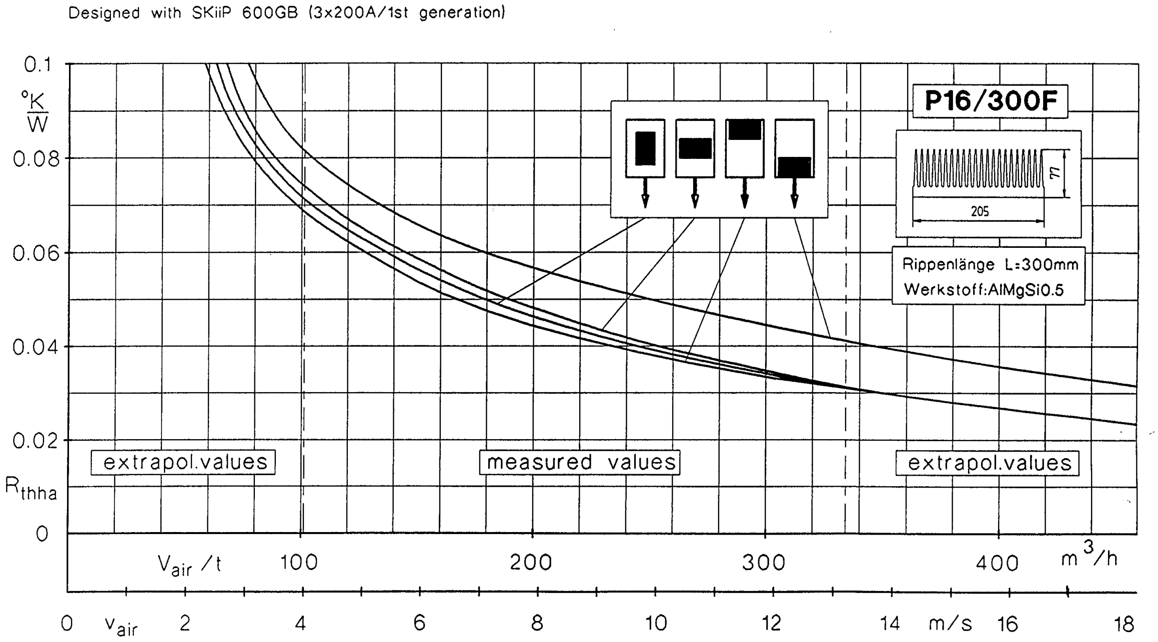


Figure 3.19 Thermal resistance of the heatsink R_{thha} of a SKiiP-assembly versus air flow and position of the SKiiPPACK on the heatsink

Figure 3.20 shows the standard assembly of a 3-fold SKiiPPACK on an air-cooled heatsink P16/280F.

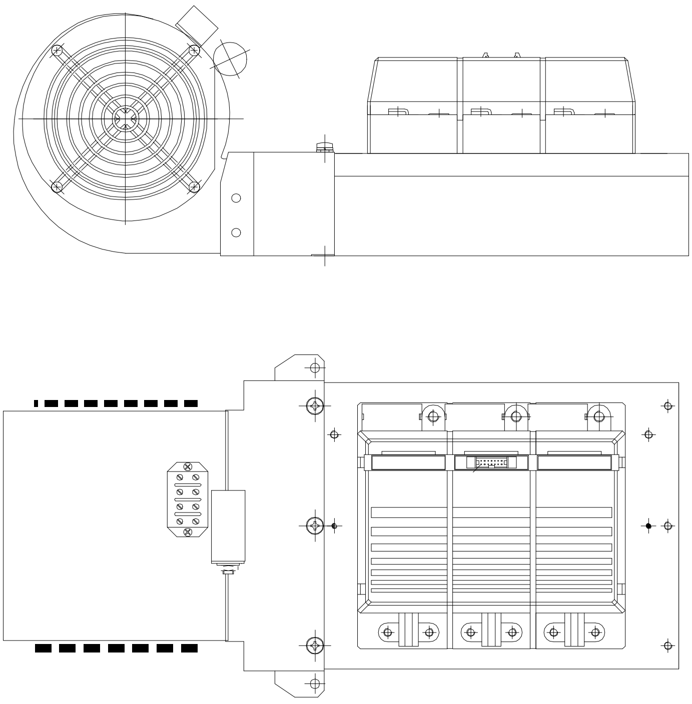


Figure 3.20 SKiiPPACK 3 standard assembly with SKF 16B fan

To determine optimized conditions for forced air cooled heatsink profiles, heat conduction and convection can also be integrated by the fin height layout, which will result in the following formula on condition of some simplifications:

$$R_{thha} = \frac{1}{n \cdot \sqrt{a \cdot U \cdot l \cdot A} \cdot \left[\frac{1}{1 + \exp - 2kh} - \frac{1}{1 + \exp 2kh} \right]}$$

with $k = \sqrt{\frac{a \cdot U}{l \cdot A}}$

(α: heat-transfer coefficient, U: fin circumference, λ: coefficient of thermal conductivity of heatsink, A: cross section of fins, h: fin height)

Often, several heatsinks have to be cooled by only one fan, for which they are either arranged in parallel (heatsinks positioned side by side) or in series (heatsinks behind each other in direction of air flow).
With regard to thermal stacking, which is preferred, for example, in three-phase inverter applications with standard GB-circuit SKiiPPACKs (halfbridge modules), special attention should be paid to the fact that the air is preheated for 2 of the 3 SKiiPPACKs, which has to be taken into consideration when determining the thermal layout.
At an air flow rate of 300 m^3/h, about 10 K temperature difference between supply and exhaust air is presupposed as a standard value per kW dissipated power. Thermal details are given in chapter 3.3.6.1.

3.3.5 Water cooling

Water cooling of power modules can be used for special high power inverters (MW-range) as well as for small power devices, which already provide for a water circuit due to their working principles (e.g. car drives, galvanic plants, inductive heating).
Mostly, the admission temperature of the coolant values is up to 50..70°C when the heat of the coolant is directly dissipated to the atmosphere; in industrial plants with active heat exchangers the temperature is about 15..25°C.

The temperature difference between heatsink surface and coolant which is lower than with air cooling may be utilized in two ways:

- increased energy exchange at a high dynamic ΔT_j of chip temperature per cycle (limits for module life see chapter 3.2.3) or
- low chip temperature, long module life.

Due to its capability for high heat retention (thermal capacity c_p = 4.187 kJ/kg $*$K) water is principally preferred to oil or glycol for the dissipation of heat.

Figure 3.21 shows a SEMIKRON standard assembly with a 3-fold SKiiPPACK on a water-cooled base plate.

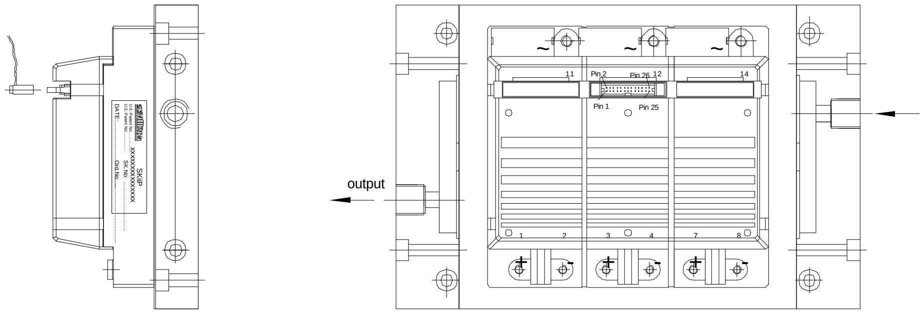


Figure 3.21 SKiiPPACK 3 standard assembly with water-cooled base plate

Due to the corrosive effect of water and the mostly required frost-resistance, open or closed circuit with pure water are hardly used.

By adding glycol, for example, the heat-retainability of the coolant will be diminished (e.g. 3.4 kJ/(kg$*$K) at an addition of 50 % glycol and a coolant temperature of 40°C). As viscosity and specific gravity of the coolant will rise, the thermal resistance from heatsink to coolant R_{thhw} will considerably increase together with the share of glycol. Compared to pure water, a 50 % addition of glycol will effect an increase of R_{thhw} by approximately 50...60 % and again by another 60...70 %, if the glycol share is increased up to 90 %.

To guarantee for corrosion protection, SEMIKRON water-cooled aluminum heatsinks contain a minimum share of glycol of 10 %. The hardness of the cooling water may not exceed a degree of 6. At least for coolant temperatures higher than 60°C we recommend to use a closed cooling circuit.

Thermal stacking of heatsinks with power modules or SKiiPPACKs is also done in correlation with water cooling. A difference of about 1.7 K per kW dissipated power between inlet and outlet temperature of the coolant can be taken as a standard value for the preheating per heatsink (SEMIKRON water-cooled heatsinks for SKiiPPACKs) for a 50/50 % water-glycol-mixture at a coolant flow of 10 l/min.

For detailed information on SKiiPPACKs on water-cooled heatsinks please see chapter 3.3.6.2.

3.3.6 Heatsink ratings for SKiiPPACKs on standard heatsinks

3.3.6.1 Forced air cooling

The following table contains the characteristics R_ν and τ_ν for thermal calculation according to the 4-time-constants-model for SKiiPPACKs on standard heatsink P16 with fan SKF 16B (GD 133-2k-40105).

$R_{thsa\ tot}$: stationary thermal resistance as a result of the temperature difference between temperature sensor (T_s) and supply air (T_a), with reference to the total power dissipation P_{tot} of the assembly

$$R_{thsa\ tot} = \sum_{\nu=1}^{4} R_\nu$$

$Z_{thsa\ tot}$: transient thermal impedance as a result of the temperature difference between temperature sensor (T_s) and supply air (T_a),with reference to the total power dissipation P_{tot} of the assembly

$$Z_{\text{thsa tot}} = \sum_{\nu=1}^{4} R_\nu \cdot \left[1 - \exp\left(-t/\tau_\nu\right]\right.$$

thermal characteristics (4-constants-model)								
R_1 K/W	R_2 K/W	R_3 K/W	R_4 K/W	ΣR K/W	τ_1 s	τ_2 s	τ_3 s	τ_4 s
2-fold SKiiPPACK (V_{air}/t = 310 m^3/h)								
$1.383\cdot 10^{-2}$	$1.886\cdot 10^{-2}$	$6.663\cdot 10^{-3}$	$3.640\cdot 10^{-3}$	$4.299\cdot 10^{-2}$	$2.579\cdot 10^{2}$	$6.350\cdot 10^{1}$	5.831	$1.543\cdot 10^{2}$
3-fold SKiiPPACK (V_{air}/t = 305m^3/h)								
$1.157\cdot 10^{-2}$	$1.669\cdot 10^{-2}$	$3.512\cdot 10^{-3}$	$3.097\cdot 10^{-3}$	$3.487\cdot 10^{-2}$	$2.638\cdot 10^{2}$	$6.625\cdot 10^{1}$	6.049	$2.000\cdot 10^{-2}$
4-fold SKiiPPACK (V_{air}/t = 300m^3/h)								
$1.398\cdot 10^{-3}$	$2.048\cdot 10^{-2}$	$7.012\cdot 10^{-3}$	$2.448\cdot 10^{-3}$	$3.134\cdot 10^{-2}$	$5.398\cdot 10^{2}$	$1.724\cdot 10^{2}$	$2.008\cdot 10^{1}$	$2.876\cdot 10^{-2}$

In the case of thermal stacking of SKiiPPACKs, the reduction of air flow resulting from the increased pressure drop and pre-heating of the “backward” SKiiPACKs by the cooling air passing the “front” SKiiPPACKs has to be considered in the calculations.
Figure 3.22 explains the principle of thermal stacking:

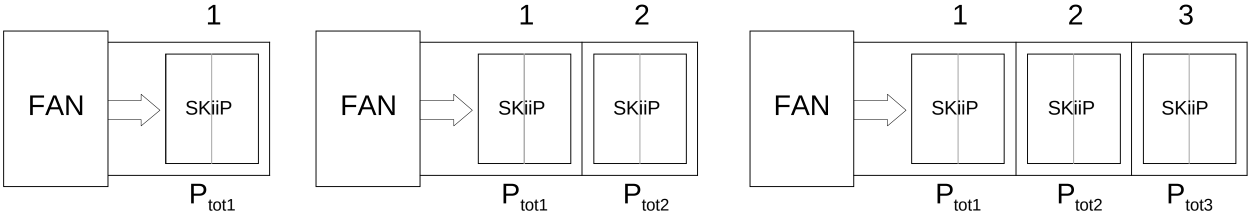


Figure 3.22 Thermal stacking of SKiiPPACKs with forced air cooling

Pre-heating is determined by total power dissipation of the SKiiPPACKs P_{totn}, stationary thermal resistance R_{thaa} and transient thermal impedance Z_{thaa} (resistance R_{thaa}/time constant τ_{aa}) between two adjacent heatsinks, see Figure 3.22. The following formulas are valid for determining the transient thermal impedances $Z_{thsatotn}$ of every single SKiiPPACK:

SKiiPPACK no. 1

$$Z_{\text{thsa tot1}} = \sum_{\nu=1}^{4} R_\nu \cdot \left[1 - \exp\left(-t/\tau_\nu\right)\right]$$

SKiiPPACK no. 2

$$Z_{\text{thsa tot2}} = \sum_{\nu=1}^{4} R_\nu \cdot \left[1 - \exp\left(-t/\tau_\nu\right)\right] + \left(P_{\text{tot1}}/P_{\text{tot2}}\right) \cdot R_{\text{thaa1-2}} \cdot \left[1 - \exp\left(-t/\tau_{aa1-2}\right)\right]$$